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Total Mass and Concentration of Particles in Dust Clouds

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FOREWORD

This document (originally issued as Revision 1 of UCRL-14397 on September 28, 1965) has been rewritten to eliminate classified information so that data relating to dust loading in clouds from nuclear explosions will become more widely available. In order to expedite the release of this document, no effort has been made to incorporate any post-1965 data, or to include up-to-date references to pertinent literature.

We suggest a most profitable area of updating might be the study of natural atmospheric solids burdens: their altitudes, concentrations, and compositions. The data to support these advances must be available in the vast NASA compilations. This information will allow a comparison to be made between the umbrella provided by a 50,000-ft thunderhead and that resulting from a nuclear burst. It is extremely unlikely that any improvement in nuclear cloud or ejecta densities or burdens will be forthcoming despite the best efforts of theoreticians. The information following is totally factual.

CONTENTS

TOTAL MASS AND CONCENTRATION OF PARTICLES IN DUST CLOUDS

ABSTRACT

The clouds from seven Pacific Proving Grounds nuclear tests and two Plowshare cratering experiments have been sampled to determine the mass loading of the clouds. The average value for the total mass of debris from surface bursts of megaton yield is 0.2 Mt mass/Mt yield; the measured particle concentration in air ranges from 6×10^{-10} to 7×10^{-9} g/cm^3. The mass of debris per unit yield from cratering explosions is about two orders of magnitude higher than is the case for surface bursts, but only a small percentage of the mass is still present in the cloud after a few minutes.

The average concentration of dust in explosion-produced clouds is in the same range as the mass concentration measured in naturally occurring high tropospheric clouds.

INTRODUCTION

A nuclear device in the megaton yield range, detonated on the surface, raises a large quantity of dust and water vapor into the stratosphere. The dust cloud from a large nuclear explosion at the Pacific Proving Grounds, for instance, contains coral from the atoll and/or seawater, plus fission products, bomb debris, and radiochemistry tracers. The bulk of the material thrown up into the cloud is accounted for by the coral and seawater. It is of interest to know the total mass of material and its concentration. Values of these quantities have been calculated with the aid of the data obtained from the radiochemical sampling program at the Pacific Proving Grounds, and are presented and discussed in this report. The effects that volatility and fractionation have on the choice of a bomb fraction indicator and on the reliability of the cloud mass calculations are briefly considered. Information is given on crater volumes and their correlation with cloud masses. The topic of dispersion in early cloud history is discussed.

The values of total mass and concentration in the dust cloud and the crater dimensions are given for seven different events in the Pacific Test Series. In addition, applicable data from two Plowshare events are included.

EXPERIMENTAL PROCEDURES

Determinations of the mass of coral and seawater were made by performing calcium and sodium analyses on the solutions derived from cloud-sampling filters. There were milligram-to-gram amounts of these elements present in the solutions, so that standard analytical techniques could be employed. Calcium was determined by oxalate precipitation and titration with standard potassium permanganate solution. Sodium was determined by flame photometry, with preliminary removal of large amounts of calcium where necessary.

The percentage of calcium (as CaO) in coral was found to vary from 50 to 55% in a series of analyses at two different sites in the Pacific Proving Grounds. The average value employed in this work was 52.6%. Accordingly, to convert from grams of calcium to grams of coral, the factor used was 2.66. The sodium content of seawater was taken to be 10.55 g/kg of seawater. In those cases where both coral and seawater were present, a correction was applied for the sodium content of coral, which is 0.24%.

A different procedure was employed for the Plowshare events. Small sections were cut from the filters, and the filter paper was burned off at low temperature in a stream of low pressure oxygen excited by a radio frequency (rf) discharge. The particles were then weighed and subjected to particle size analyses by sedimentation methods[1].

It is, of course, necessary to know what fraction of the total material the filter sample represents. For the samples from the tests in the Pacific, curium, which was present in the device and determined radiochemically in the filter sample, was used as the "bomb fraction" indicator. For the Plowshare events, residual fissile material (uranium and/or plutonium) served the same purpose. This bomb fraction can be a useful value only if the indicator really traces the most predominant chemical species (e.g., CaO from coral and Na_2O from seawater); i.e., if there is no fractionation. The subject of fractionation and the basis for choosing curium or plutonium as bomb fraction indicator will be examined in the next section.

VOLATILITY AND FRACTIONATION

Qualitatively the phenomenon of fractionation of fission products and other bomb debris has been understood for a long time. The quantitative aspects, however, require thermodynamic and phase-relationship data which are either completely unknown or poorly documented. Briefly, the model which seems to fit the observations requires that particles form the condensed phases when the "bulk" or most predominant chemical species condense. At that time all the similar and more refractory species are condensed. At later times, as cooling progresses, the more volatile species condense on the surface of particles. Since the surface-to-mass ratio of the particles varies inversely with the particle size, the more volatile species are concentrated on the small particles. Thus one would expect that, all other things being constant, more volatile species would be enriched at higher altitudes at any time, and at any altitude more volatile species would be enriched at later times.

When attempts are made to put this into quantitative terms, difficulties arise. Most important is the fact that "volatility," or more precisely the vapor pressure in equilibrium with the condensed phase for any element or compound of that element, is neither independent of the other elements nor of the nature of the condensing phase. For example, condensing NaCl, SiO_2, or CaO would not necessarily carry the same fraction of MoO_2 under identical conditions of concentration and oxygen pressure, and for the same condensing phase different amounts of MoO_2 would be carried by different concentration and oxygen pressure ratios.

Figure 1 is reproduced from a paper[2] discussing only the effect of temperature and oxygen pressure. All species are supposed to be independent (i.e., no solid solutions or binary compounds are permitted), and all are in the same atomic abundance. The line indicates the vapor pressure of UO_2 at the same temperature. From these data and calculations, we would expect that all of the elements lying above the UO_2 line would be depleted in the larger particles and enriched in the smaller particles. This is not the observed case, however, because UO_2 is not the matrix phase if the cloud contains much larger amounts of some other compound, for example CaO. At this temperature (2500K) the vapor pressure of CaO might be about 10^{-4} atmospheres. In bomb debris from a surface burst the ratio of concentration

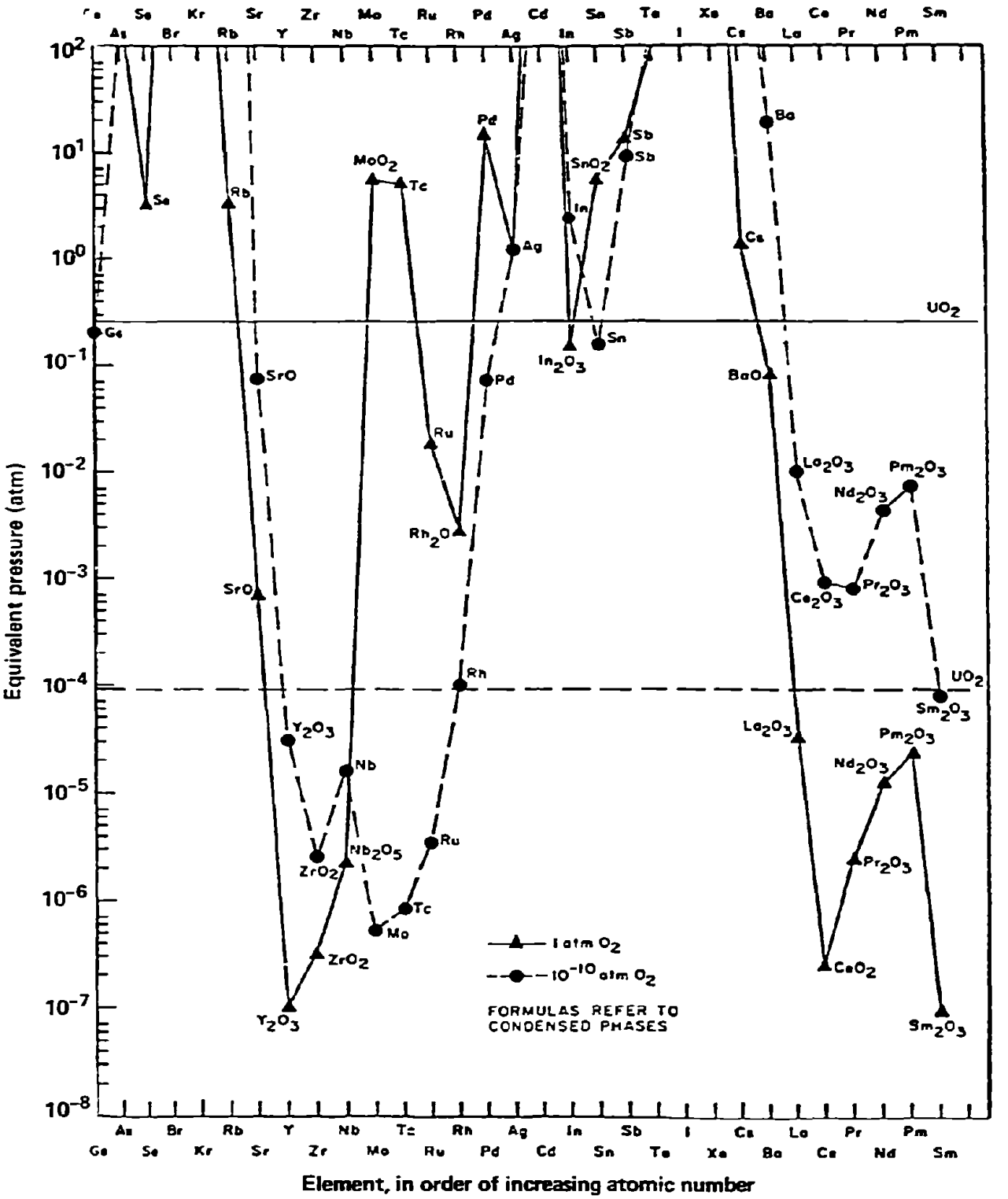

Figure 1. Equivalent pressures of fission products in equilibrium with their condensed phases at 2500 K.

of CaO to the sum of all other materials might be 10^3 to 10^5. Thus, we would expect that only the most refractory species would condense uniformly with the CaO matrix, and all other elements would be fractionated to a greater or lesser degree. On the other hand, if the condensing phase is Na_2O (not shown on the figure) and the same concentration ratios apply, all of the elements and compounds with pressures lower than UO_2 or U_3O_8 would be uniformly included in the particles.

For these reasons, the only species which can be trusted to represent the mass matrix in clouds of various origin is the most refractory one. Since curium and plutonium generally behave as such refractory species and are present in most of the cases for which data are available, the curium or plutonium bomb fraction has been used to determine the total material present. If the "fission fraction," usually determined with ^{99}Mo, is used to determine the total mass, it would be expected that a much larger scatter would be observed between samples collected at various times and altitudes. Smaller calculated masses would generally be expected at later times and higher altitudes. The best internal test of the validity of measurement is that there be no correlation between time, altitude, and calculated total debris mass. This test is applied to the data in the sections on Weapons Test and Plowshare data.

A second type of fractionation can occur. In this case, completely inert particulate material is swept into the cloud and stem by the rising air mass. It can correctly be argued that the particles of this material are not traced by the debris at all and that the particle size distribution (and hence fallout rate) can be quite different from that of the traced material. There is no way to estimate the importance of this effect, except by comparing samples collected at varying times and altitudes, and by comparing the mass of material scoured from within the crater to the total mass calculated by internal tracer methods.

WEAPONS TEST DATA: CLOUD MASSES AND PARTICLE CONCENTRATIONS

From the weight of the calcium and sodium in the filter-sample solution and the bomb fraction (determined by the methods previously described), the total mass of material thrown up into the cloud can be calculated. An

estimate of the concentration of the material in the cloud at sampling time, in the particular portion of the cloud that was sampled, is obtained in the following manner. From the sampling data, the speed of the aircraft and the time spent in the cloud are known. With these values and the effective orifice of the sampling equipment, the volume sampled is calculated, assuming laminar flow. The mass of the material on the filter divided by the volume sampled gives an estimate of the concentration.

The yields of the devices used in the calculations are the total yields, including fission and fusion yields; each is a concensus based on results from several different physical and radiochemical measurements.*

Let us examine in detail the data and calculations for some typical events. Table 1 gives results for the Apache Event, in which the device was detonated on a barge in deep water. There was no crater, and no calcium was found in the solutions, so that only sodium was determined. Samples 3 and 6 were taken at high altitude along the edges of the cloud, whereas the other samples were taken in the center. It is clear from this tabulation that the calculated total debris mass is relatively constant and independent of sampling time, altitude, or the portion of the cloud which was sampled. Similarly, if we calculate the mass of sodium per fission, we find the standard deviation for the average value of the samples is ~13%, showing that in this case there has been no fractionation of the sodium and the ^{99}Mo used to obtain the fission numbers.

Table 2 gives concentration values for the same event and samples. The concentration at the edge of the cloud and at high altitude is somewhat lower, as we would expect. Still, the range of concentrations is not large, and nicely centered around 4.2×10^{-9} g/cm^3.

Data for the Zuni Event, in which the device was detonated on coral, are collected in Tables 3 and 4. Here, it was necessary to determine only calcium. Here again the total debris mass is quite constant and independent of sampling time and altitude, even though the ratio of the mass of coral per fission is lower for the late, high-altitude samples 3 and 7. The lower ratio indicates that there was enrichment of the more volatile MoO_2 with respect to CaO at later times and higher altitudes. We can also get a measure of the

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* All device yields in this report were taken from Ref. 3.

Table 1. Total debris mass, Apache Event.[a]

Sample	Altitude (thousands of feet)	Time after detonation (hr:min)	kg seawater / Mt yield	Notes
1	38.5	1:31	3.2×10^{8}	
2	42.5	1:39	3.0×10^{8}	
3	50.5/53.5	2:04	2.8×10^{8}	West edge
4	48	2:01	3.2×10^{8}	
5	51.5	2:26	2.6×10^{8}	
6	50/54	2:57	2.7×10^{8}	East edge
		Average	2.9×10^{8}	
		σ =	0.24×10^{8}	

[a] Location: Barge, deep water.

Table 2. Concentration of seawater in cloud, Apache Event.

Sample	Altitude (thousands of feet)	Time after detonation (hr:min)	Volume sampled (cm^3)	Concentration of seawater in cloud (g/cm^3)	Notes
1	38.5	1:31	7.6×10^{9}	6.2×10^{-9}	
2	42.5	1:39	5.2×10^{9}	4.9×10^{-9}	
3	50.5/53.5	2:04	3.8×10^{9}	2.6×10^{-9}	West edge
4	48	2:01	5.8×10^{9}	6.1×10^{-9}	
5	51.5	2:26	5.9×10^{9}	3.5×10^{-9}	
6	50/54	2:57	3.7×10^{9}	2.1×10^{-9}	East edge
			Average	4.2×10^{-9}	

Table 3. Total debris mass, Zuni Event.[a]

Sample	Altitude (thousands of feet)	Time after detonation (hr:min)	Mass of coral (g)	Mass of coral/ fission[b]	kg coral/ Mt yield	Notes
1	44/50	1:57	2.5×10^{11}	1.4	7.5×10^{7}	Two filters from same aircraft
5	44/50	1:57	2.7×10^{11}	1.4	$7.6\ 10^{7}$	
3	54/56	2:50	2.8×10^{11}	1.0	8.0×10^{7}	Two filters from same aircraft
7	54/56	2:50	2.6×10^{11}	1.0	7.4×10^{7}	
2	43	1:51	2.6×10^{11}	1.4	7.4×10^{7}	Different aircraft
6	43	1:51	2.7×10^{11}	1.4	7.7×10^{7}	
4	51	2:18	2.6×10^{11}	1.5	7.5×10^{7}	
				Average	7.5×10^{7}	
				=	0.3×10^{7}	

[a] Location: Ground; yield: 3.5 Mt.
[b] Normalized to samples 3 and 7.

Table 4. Concentration of coral in cloud, Zuni Event.

Sample	Altitude (thousands of feet)	Time after detonation (hr:min)	Volume sampled (cm^3)	Concentration of coral in cloud (g/cm^3)	Notes
1	44/50	1:57	7.0×10^{9}	4.5×10^{-9}	Two filters from same aircraft
5	44/50	1:57	7.0×10^{9}	4.7×0^{-9}	
3	54/56	2:50	1.1×10^{10}	0.6×10^{-9}	Two filters from same aircraft
7	54/56	2:50	1.1×10^{10}	0.6×10^{-9}	
2	43	1:51	4.3×10^{9}	3.0×10^{-9}	Different aircraft
6	43	1:51	4.3×10^{9}	2.8×10^{-9}	
4	51	2:18	5.3×10^{9}	2.0×10^{-9}	
			Average	2.6×10^{-9}	

Table 6. Summary of total debris mass and particle concentration for Pacific Proving Grounds events.

Event	Yield (Mt)	Location	kg coral/ Mt yield	kg seawater/ Mt yield	Total material (kg/Mt)	Concentration in air (g/cm^3)
LaCrosse	0.040	Ground	2.9×10^7 ($\sigma = 0.17\times10^7$)	--	2.9×10^7	3×10^{-11} to 3×10^{-10}
Koon	0.11	Ground	4.6×10^8 ($\sigma = 0.5\times10^8$)	--	4.6×10^8	No data
Mohawk	[a]	Tower	6.5×10^6 ($\sigma = 2.9\times10^6$)	--	6.5×10^5	$2 - 6\times10^{-10}$
Apache	[a]	Barge, deep water	--	2.9×10^8 ($\sigma = 0.2\times10^8$)	2.9×10^8	$2 - 6\times10^{-9}$
Zuni	3.5	Ground	7.5×10^7 ($\sigma = 0.3\times10^7$)	-- --	7.5×10^7	$0.6 - 4.7\times10^{-9}$
Tewa	5	Barge, shallow water	3.9×10^7 ($\sigma = 0.3\times10^7$)	7.2×10^7 ($\sigma = 0.8\times10^7$)	1.1×10^8	$1 - 7\times10^{-9}$
Bravo	15	Ground	1.2×10^8 ($\sigma = 0.1\times10^8$)	1.0×10^8	2.2×10^8	No data

[a] yield is classified.

The other events of the Pacific Test Series that were studied fall in line with the examples that have been discussed. Table 6 summarizes the calculations of the total debris mass per megaton of yield and the particle concentrations in the cloud. Each value is an average of four to six determinations. The standard deviations for a single measurement (σ) are given in each case. Note that the low mass of debris for the Mohawk Event and that the much greater than average uncertainty may be accounted for by the fact that the device was detonated on top of a tower. If we consider the four events in the megaton yield range, plus Koon, we arrive at an overall mean value of 2.3×10^8 kg/Mt, which is equal to 0.23 Mt mass/Mt yield. The standard deviation of the mean is 0.05 Mt/Mt. The particle concentration in air ranges from 6×10^{-10} to 7×10^{-9} g/cm^3.

How accurate are these numbers? The calcium and sodium determinations were done by standard analytical techniques and are good to better than 1%. Assumptions regarding the calcium content of coral should not produce an error of more than 5%. It has been shown that curium is a good bomb-fraction indicator and that the agreement in the total debris mass between samples from the same event is better than 10% in every case except one. The yields are

internal consistency of the measurements and the sampling operation. Samples 1 and 5, as well as 3 and 7, are from two filters taken from the right and left wing samplers of the same aircraft. Samples 2 and 6 come from different aircraft that sampled the same portion of the cloud. The agreement is very good.

Table 4 further shows the agreement between "duplicate" samples. As expected, the concentration of coral at later time and higher altitude is lower. The range of concentrations is 0.6–4.7 $\times 10^{-9}$ g/cm^3.

Although the La Crosse Event featured a low-yield device (40 kt), some interesting information can be obtained from it on the consequences of sampling in cloud areas of high intensity and low intensity. Data for the total debris mass from this event are shown in Table 5. The average cloud intensities are those reported by the pilots of the sampling aircraft. It can be seen that, although the average cloud intensities vary by as much as a factor of 15, the calculated total debris mass remains relatively constant. These data demonstrate once more that curium is a good cloud mass indicator. The concentrations in the clouds for this event ranged from 5 $\times 10^{-11}$ to 3 $\times 10^{-10}$ g/cm^3.

Table 5. Total debris mass, LaCrosse Event.[a]

Sample	Altitude (thousands of feet)	Time after Detonation (hr:min)	Average cloud intensity (R/hr)	Mass of coral (g)	kg coral/ Mt yield
1	28.5/35	2:01	1.7	1.3×10^{9}	3.1×10^{7}
2	22.5	1:31	20	1.1×10^{9}	2.8×10^{7}
3	23	2:20	3.5	1.1×10^{9}	2.8×10^{7}
4	22.5	2:20	25	1.2×10^{9}	3.0×10^{7}
				Average	2.9×10^{7}
				σ =	0.2×10^{7}

[a] Location: Ground Yield 0.040 Mt

known to 15% or better. It thus seems fair to state that the individual total debris masses are known to better than ± 50%, and the mean value is good to ± 20%.

The particle concentrations in air are subject to somewhat greater uncertainty. Although the mass of material on the filter paper is accurately known, the aircraft sampling data are not as reliable and the error that is introduced by assuming laminar flow is not known. However, it is believed that the concentrations are certainly of the correct order of magnitude.

In theory, one could use ^{238}U to determine the amount of coral or seawater. Coral contains from 1 to 5 ppm of ^{238}U, and the uranium content of seawater is 2.5 μg/ℓ. In practice, there are a number of objections. The ratio of ^{238}U to coral is small and varies from site to site and with depth of coral. Uranium and calcium do not condense together and there is frequently severe fractionation. Finally, there were large amounts of ^{238}U in the devices, in comparison with which the uranium contribution of the coral was small. This approach must therefore be considered unreliable.

DATA: PLOWSHARE EXPERIENCE

Two Plowshare events which furnished applicable data will be considered. The first was Sedan, a nuclear cratering experiment at 635 ft below the surface, with a yield of 0.1 Mt. The second was Palanquin, with a depth of burial of 280 ft and a yield of 4.3 kt. If we calculate the total mass of debris from aircraft samples and fallout samples in the same manner as before, we obtain the results shown in Table 7. The masses are obviously much greater than those for surface bursts, but cloud altitudes are low. Underground bursts raise large volumes of material to low altitudes, whereas surface bursts expend much of their energy in heating air.

It must be understood, however, that only a fraction of Sedan's total debris mass ever got into the cloud; the rest immediately fell back into the crater. It is estimated that about 15% of the total material was in the cloud during the first minute, and that after 30 minutes only about 4% remained. Accordingly, 30 minutes after detonation, we expect approximately 6.5×10^7 kg ($= 6.5 \times 10^8$ kg/Mt = 0.65 Mt/Mt) total debris actually in the cloud, whose top is at 12,000 ft above the terrain.

Table 7. Debris mass, Plowshare Events.

Sample	Altitude above terrain (thousands of feet)	Time after detonation (hr:min)	Total debris mass (kg)	kg mass/ Mt yield
A. Event: Sedan	**Depth: 635 ft**		**Yield: 0.10 Mt**	
Aircraft 1	9	0:08	1.3×10^{9}	1.3×10^{10}
Aircraft 2	7	1:15	1.9×10^{9}	1.9×10^{10}
Fallout samples[a]		Average	1.6×10^{9}	1.6×10^{10}
		Average	1.6×10^{9}	1.6×10^{10}
Estimated mass actually in cloud at H + 0:30, $6.5\ 10^{7}$ kg = 6.5×10^{8} kg/Mt				
B. Event: Palanquin	**Depth: 280 ft**		**Yield: 0.0043 Mt**	
Aircraft A	5.3	0:11-0:16	6.6×10^{7}	1.5×10^{10}
Fallout samples		Average	6.3×10^{7}	1.4×10^{10}
Estimated mass actually in cloud at H + 0:14 to H + 1:33, 5×10^{5} kg = 1.1×10^{8} kg/Mt.				

[a] Average of six trays located upwind, crosswind, and downwind to 7 miles.

For Palanquin, estimates of total cloud volume at the various sampling times were made.* The volume of air sampled divided by the cloud volume gave a cloud fraction. From this and the weight of material on the filter, the mass of material actually in the cloud was computed. The mean value at times from 14 to 93 minutes after detonation was $5\ 10^{5}$ kg (= $1 \cdot 10^{8}$ kg/Mt = 0.1 Mt/Mt). The top of the cloud was about 5500 ft above the terrain at sampling time.

Table 8 shows data for particle concentrations in the cloud for the Sedan and Palanquin Events. The concentration drops rapidly (roughly as $1/t^{2}$) and after 90 minutes approaches the magnitude of the concentrations in the clouds

* Estimates considered to be good to about a factor of 2 were prepared by J. B. Knox (G-Division, LLNL).

Table 8. Particle concentrations, Plowshare Events.[a]

Sample	Altitude above terrain (thousands of feet)	Time after detonation (hr:min)	Volume sampled (cm^3)	Concentration of debris in cloud (g/cm^3)
Sedan 1	9	0:08	2.1×10^{8}	4.2×10^{-7}
Sedan 2	7	1:15-1:37	6.3×10^{9}	7.6×10^{-9}
Palanquin A	5.3	0:11-0:16	6.0×10^{8}	7.6×10^{-8}
Palanquin C	4.8	1:01-1:33	4.4×10^{9}	1.9×10^{-8}

[a] See also Ref. 4.

from surface bursts (on the order of 10^{-8} g/cm^3). It is of interest to note that the aircraft sampling the Sedan cloud at 8 minutes after detonation reported that the window and paint on the nose of the aircraft were sandblasted and the pilot had some trouble seeing on the way home. The particle concentration in the cloud at that time is calculated to be 4×10^{-7} g/cm^3. Later sampling missions on Sedan and sampling aircraft on Palanquin experienced no difficulties.

Particle-size studies on the aircraft samples from Sedan and Palanquin, carried out under the direction of Dr. Robert Heft, show a particle size range of 0.5-100 μ, with average diameter for Sedan 28 μ and for Palanquin 21 μ. X-ray analysis shows that the particles are orthoclase: $K_2O \cdot Al_2O_3 \cdot 6SiO_2$, specific gravity 2.56. Radioactivity from nuclides of the more refractory elements (like zirconium and plutonium) is concentrated in the coarse (average particle size) fraction, where the bulk of the debris is found.

CORRELATIONS OF CRATER VOLUMES

The craters produced by near-surface detonations are formed by three dominant mechanisms: (1) compaction and plastic deformation, (2) spallation, and (3) gas erosion. Nordyke[5] has discussed the relative importance of these three modes in qualitative terms and concludes that, for near surface

bursts, mechanism (1) accounts satisfactorily for the entire apparent void created. Figure 2 is his graphic presentation of the relative contributions of these mechanisms as a function of depth of burial. This kind of analysis indicates only that a small fraction of the crater volume will appear as airborne material; it does not indicate quantitatively what is ejected in the cloud. Therefore it is assumed that about 1% of the crater-volume material might be airborne. Detonations buried at greater scaled depths produce relatively more airborne material, and relatively less volume is produced by compaction and plastic flow. The ejecta and fallout studies of Sedan (100 kt buried 635 ft in dry alluvium) allow the distribution of volume[4] shown in Table 9.

Even though the Sedan crater was produced by mechanisms significantly different from craters purduced by surface bursts, only about 1% of the crater volume appeared as longer range (or time) fallout. From studies of the missile splash craters[4] it can be shown that essentially all of the ejecta were on the ground before the last missiles impacted. From range-angle studies the largest time of missile flight was about 1 minute; therefore, it can be inferred that essentially all of the ejecta were deposited in less than 1 minute.

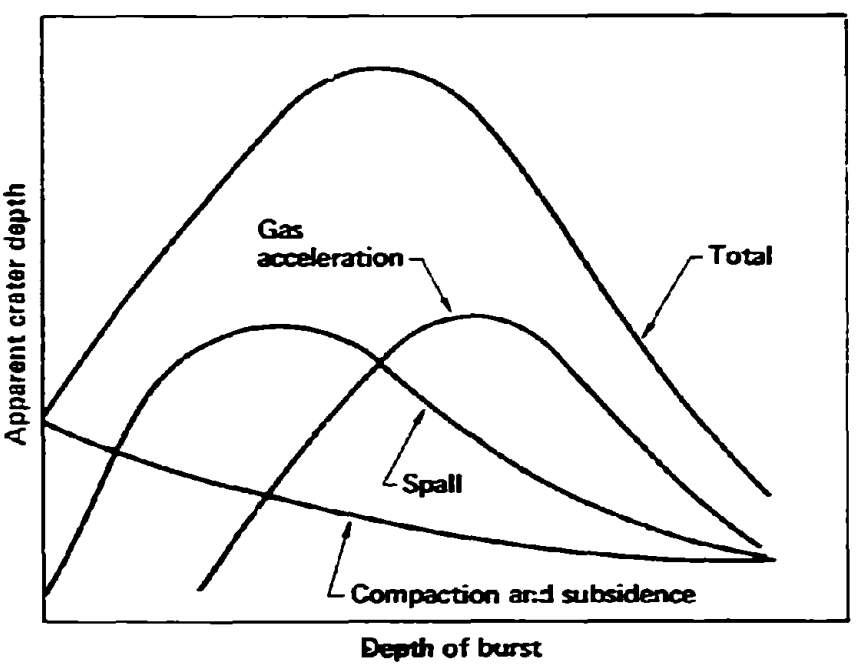

Figure 2. Relative importance of various cratering mechanisms as a function of depth of burst.

Table 9. Apportionment of Sedan Crater volume.[a]

Region	Mass (g)	Percent of total
Ejecta (close-in)	4.5×10^{12}	59
Fallout (dust)	6.5×10^{10}	0.8
Compaction and plastic deformation	3.1×10^{12}	40
Total	7.6×10^{12}	100

[a] See also Ref. 4.

Table 10. Volume and related preshot mass of several craters.

Event	Medium	Volume (ft^3)	Crater mass (g)	Inferred cloud mass (g)
Bravo[a]	Coral	3.4×10^{9}	2.2×10^{14}	2×10^{12}
Koon	Coral	1.0×10^{7}	6.5×10^{11}	6×10^{9}
LaCrosse	Coral	2.8×10^{6}	1.8×10^{11}	2×10^{9}
Zuni	Coral	2.8×10^{8}	1.8×10^{13}	2×10^{11}
Mohawk[b]	Coral	5.6×10^{6}	3.6×10^{11}	4×10^{9}
Apache	Water	No permanent crater		
Tewa	Coral	8.1×10^{8}	5.2×10^{13}	5×10^{11}
Sedan[c]	Desert alluvium	1.8×10^{8}	7.6×10^{12}	7×10^{10}
Palanquin[d]	Rhyolite	1.3×10^{6}	8.1×10^{10}	8×10^{8}

[a] The Bravo data are suspect and probably not good to better than a factor of 2.
[b] Because Mohawk was fired on a tower, the efficiency for crater formation is markedly reduced.
[c] Sedan was fired 635 ft below ground surface at about optimum depth for crater production.
[d] Palanquin was fired at the limit depth for containment and an erosional crater was produced.

The craters produced by several detonations at the Pacific Proving Grounds have been resurveyed and data from previous surveys assembled.[6] These data are summarized in Table 10 along with an estimate of the mass of material in the associated clouds. This cloud mass is estimated assuming 1% of the total mass equivalent to the crater volume will be airborne for times greater than approximately a minute.

DISPERSION IN EARLY CLOUD HISTORY

To determine the particle concentrations once the total mass is known, one must estimate or measure the effective cloud volume. In actuality, a cloud produced by ejecta and dust is very nonuniform, but some average concentration or volume can be calculated by sampling one complete traverse, thus averaging the inhomogeneity. A second way to calculate the particle concentration is to divide the expected airborne mass by an expected cloud volume. It must be recognized that point to point densities will vary an order of magnitude around such an average.

The initial stabilized cloud volume expected from surface and subsurface detonations has been discussed in detail by Knox.[7] In this work, the cloud height, diameter, etc., are compared to a series of nondimensional scaling parameters. Figures 3, 4, and 5 can be used to compute main cloud volumes for various depths of burst and yield. These graphs are reduced to a "neutral" atmosphere model and have been empirically developed from cloud size measurements. Clouds produced by detonation in other media will be approximately the same <u>if</u> the water content is not grossly different. Very dry media (<1% H_2O) have been shown to yield considerably smaller clouds.

With these figures, the initial stabilized cloud volume for megaton surface bursts will be about 4×10^{18} cm^3. This volume will increase as the cloud spreads under the influence of diffusion and convection. When one assumes only radial dispersion, the equation representing these effects is approximately

$$V_t = 6.3 \times 10^5 tH,$$

with H in meters, V_t in cubic meters, and t in seconds. Using these inputs, we have calculated an initial cloud concentration from the estimated apparent

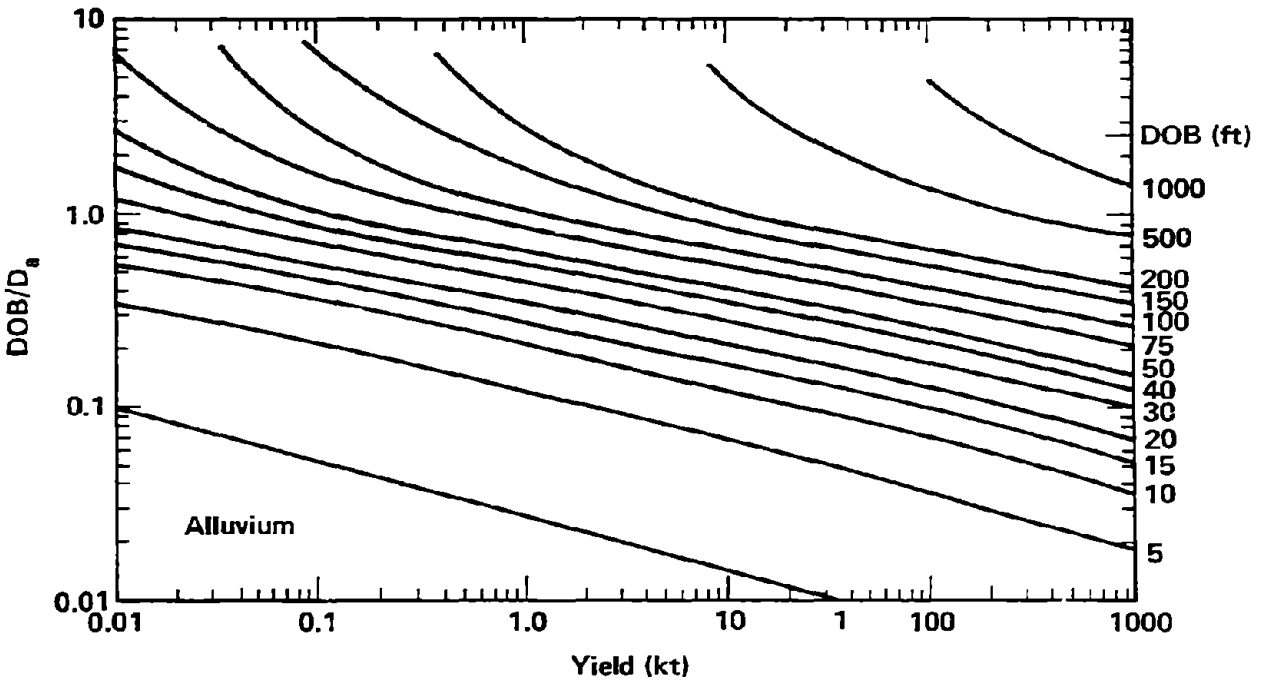

Figure 3. Computational aid to the acquisition of input data to cloud dimension graphs of Figs. 4 and 5.

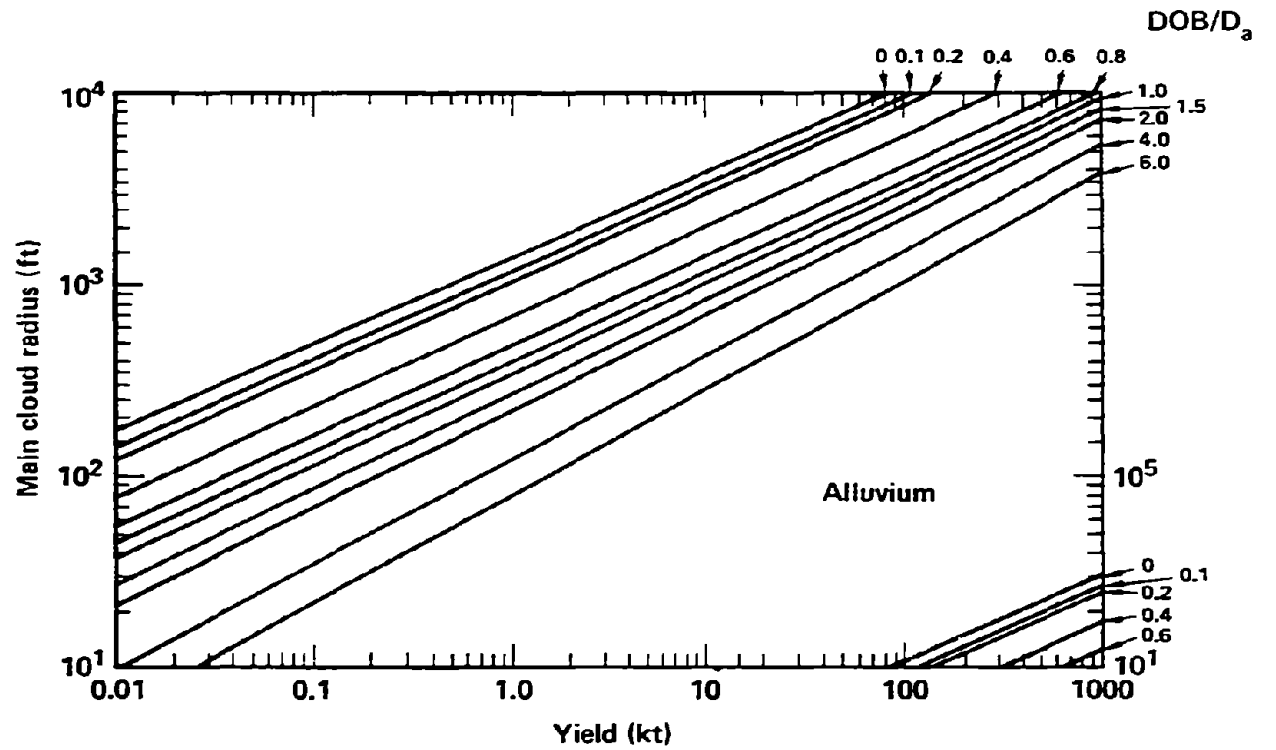

Figure 4. Main cloud radius as a function of yield (total) and parameter DOB/D_a (alluvium).

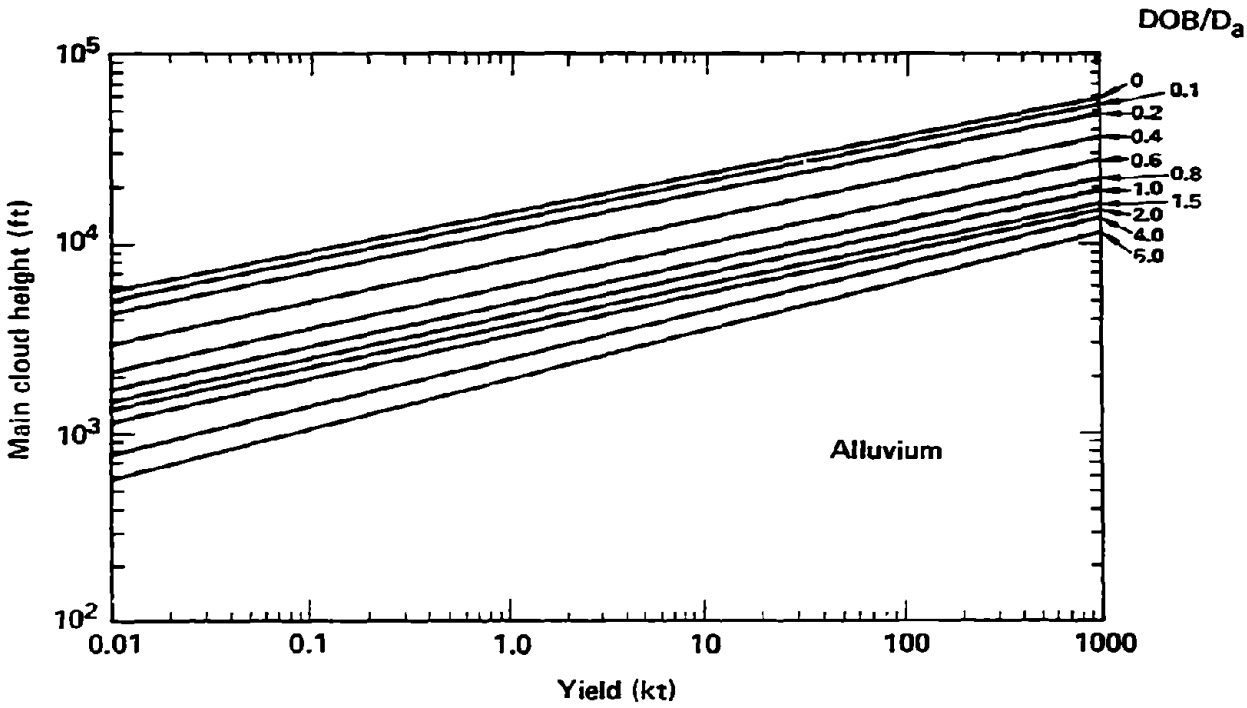

Figure 5. Main cloud height as a function of yield (total) and parameter DOB/D_a (alluvium).

masses calculated in Table 10. Later-time concentrations can then be calculated and compared to the aircraft sampling data summarized in Tables 1 through 8. Table 11 is a summary of calculated initial concentrations and measured concentrations corrected back to cloud stabilization time (t = 5 minutes).

In the case of surface bursts, the fallout during the first few hours will not significantly reduce (i.e., by a factor of 2 or more) the particulate concentrations. For subsurface detonations, however, because the fallout rate is faster and the heights are an order of magnitude less, fallout rapidly depletes the cloud. Thus, for subsurface bursts, calculations at later times must contain some consideration of fallout. Comparison of the calculated initial concentrations above with the measurements made at later times can give some idea of the magnitude of correction. Correcting for diffusion alone would lead to about 1/10 of the initial concentration after 1 hr, 1/20 after 2 hr, and 1/40 after 4 hr.

Values for the mass concentration in the cloud at times from 1 to 4 hr are then in the range 1×10^{-9} g/cm^3 to 2×10^{-10} g/cm^3. For surface bursts these are not in disagreement with values derived from aircraft sampling.

Table 11. Comparison of calculated initial concentration obtained from cloud volumes at stabilization time (t = 5 minutes) and measured concentrations corrected back to t = 5 minutes.

Event	Calculated cloud volume (cm^3)	Calculated initial concentration (g/cm^3)	Measured concentration to t_0 (g/cm^3)
Bravo	1.1×10^{20}	2.0×10^{-8}	--
Koon	8.7×10^{17}	0.7×10^{-8}	--
LaCrosse	1.3×10^{17}	1.4×10^{-8}	0.4×10^{-8}
Zuni	1.6×10^{19}	1.1×10^{-8}	6×10^{-8}
Tewa	2.5×10^{19}	2.1×10^{-8}	1.2×10^{-8}
Sedan[a]	4.5×10^{15}	1.7×10^{-5}	1×10^{-6}
Palanquin	1.1×10^{14}	7.4×10^{-6}	5×10^{-7}

[a] Note that these volumes are normalized to neutral atmospheres; the Sedan cloud was actually about five times larger.

SUMMARY AND CONCLUSIONS

The average value for the total mass of debris from bursts of megaton yield in the Pacific is 2×10^{8} kg/Mt or 0.2 Mt mass/Mt yield. The particle concentration in air ranges from 6×10^{-10} to 7×10^{-9} g/cm^3. The mass of debris per megaton of yield is about two orders of magnitude higher for underground bursts, but only a fraction of this enters the cloud, and only a small percentage of the mass is still present in the cloud after a few minutes. The early particle concentrations for subsurface bursts are also higher, but after 90 minutes the magnitude has dropped to 10^{-8} g/cm^3. The clouds did not rise more than 12,000 ft above the terrain for Sedan, and 5,500 ft above the terrain for Palanquin. Average particle diameter is 21-28 μ, and the material from underground bursts found in the cloud was identified as orthoclase: $K_2O \cdot Al_2O_3 \cdot 6SiO_2$.

The range of concentration of dust in explosion-produced clouds is not outside the range of high tropospheric cloud mass concentrations (see Appendix A).

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APPENDIX A. NATURAL PARTICLE CONCENTRATIONS IN THE HIGH TROPOSPHERE

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Clouds above 25,000 ft will usually be composed entirely of ice crystals, and the total solid water content will not exceed 10^{-7} g/cm^3. If both water and ice are present in clouds above 25,000 ft, the water content will be between 10^{-7} and 10^{-6} g/cm^3. In cumulo-nimbus clouds, the water content may occasionally reach 10^{-5} g/cm^3 (Ref. A1). These are best estimates based on very limited data at these heights.

On page 19-3 of Ref. A1 there appears an example of a B-47 contrail with an excess moisture concentration of 0.6 g of water per kilogram of dry air. Assuming that this appears as ice and that the B-47 was flying at a pressure altitude of 250 mbar (the usual operating height for a B-47), and using the stated flight level temperature of -67°C, it is possible to compute the water content of this contrail. This water content is 2.5 10^{-7} g/cm^3.

Mee summarizes cloud particle samples collected on 15 jet flights at altitudes of 25,000 to 40,000 ft between Edwards AFB and Reno.[A2] These data were on cirrus clouds whose particle concentrations were too small to be visible either from the ground or from the aircraft. Typical particle concentrations were found to range from 20 to 100 particles/cm^3. Ice crystal sizes were mostly less than 10 μ, with occasional well-formed prismatic crystals up to 200 μ or more in length. If you take an average concentration of 60 particles/cm^3 and an average diameter of 10 μ and assume unit density, water content of 3 10^{-8} g/cm^3 results. Although several flights were above the tropopause, no particles were detected in this region.

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